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RELIABILITY AND REDUNDANCY CONSIDERATIONS IN SELECTING SPACECRAFT BATTERIES

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SUMMARY

The electrical storage battery of a spacecraft ordinarily consists of two or more parallel-connected groups of series-connected cells. The number of such groups can be varied over a considerable range depending on cell size and degree of redundancy. This paper gives a mathematical approach to the problem of choosing a configuration with maximum reliability.

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INTRODUCTION

One of the problems in designing a spacecraft power supply is the selection of a suitable configuration for the cells which form the electrical storage battery. The usual practice is to connect in series the number of cells necessary to obtain the desired voltage; two or more of the "strings" thus formed are then connected in parallel to form the battery. In some instances the number of parallel strings is dictated by system constraints or some extraneous consideration. In other cases, however, the designer is free to choose the number of strings, provided that he makes a suitable choice of cell capacity. It is the purpose of this paper to help the designer make an optimum choice.

THE NUMBER OF PARALLEL STRINGS

The approach used is purely mathematical and is based on the following assumptions, none of which is strictly true:

1. The probability (P) that a given string will survive at least to a given time (t) is independent of the size of the cells it contains, i.e., there is no inherent quality difference between large and small cells;

2. The several strings are independent in the sense that failure of one or more does not influence the expected lifetime of those remaining;

3. The total number of strings (n) includes a number (k) of redundant strings, and no more than k strings can fail without leading to immediate failure of the system.

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The probability $(R_{n,k})$ that at most k out of n strings will fail before a time t is then given by

$$R_{n,k} = \sum_{i=0}^{k} \frac{n!}{(n-i)!\,i!} P^{n-i} (1-P)^{i}, \tag{1}$$

where i is the term number, and of course $0! = 1$.

The quantity $R_{n,k}$ can be identified with system success. It is plotted against P in Figures 1 and 2. Figure 1 shows the effect of varying n while holding the ratio n/k constant. Figure 2 shows the effect of varying this same ratio with n constant.

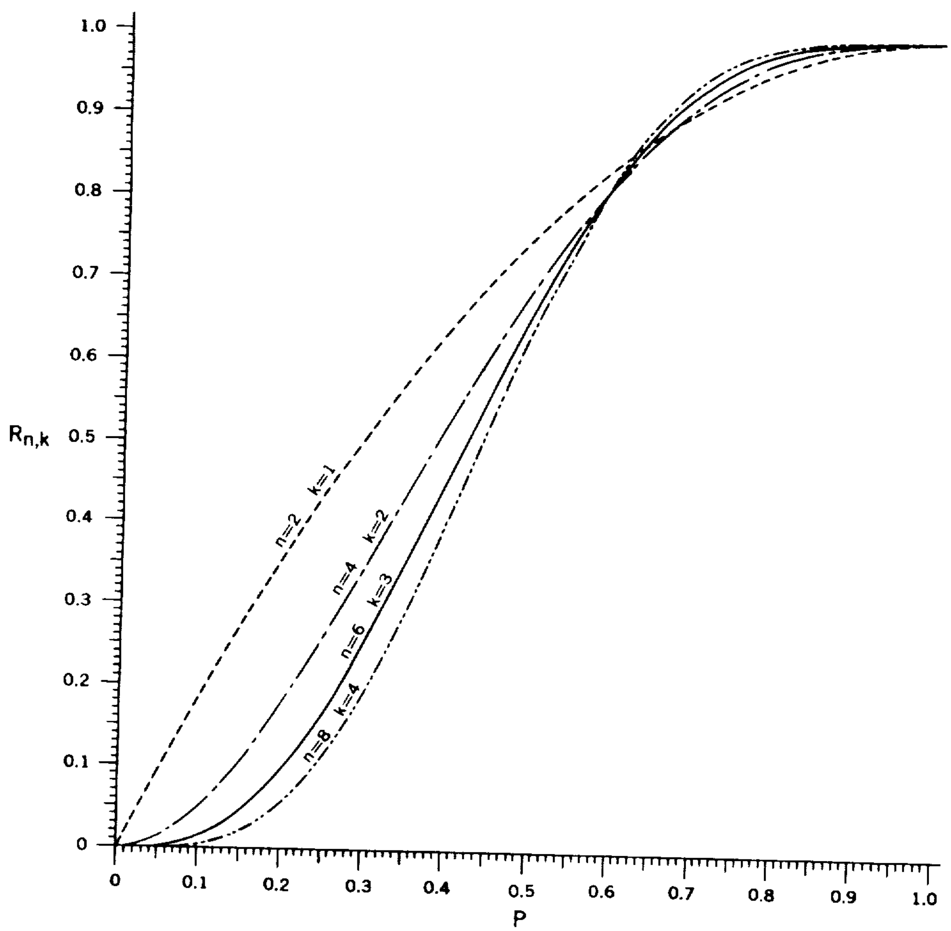

Figure 1—$R_{n,k}$ as a function of P for a varying value of n and a constant value of n/k

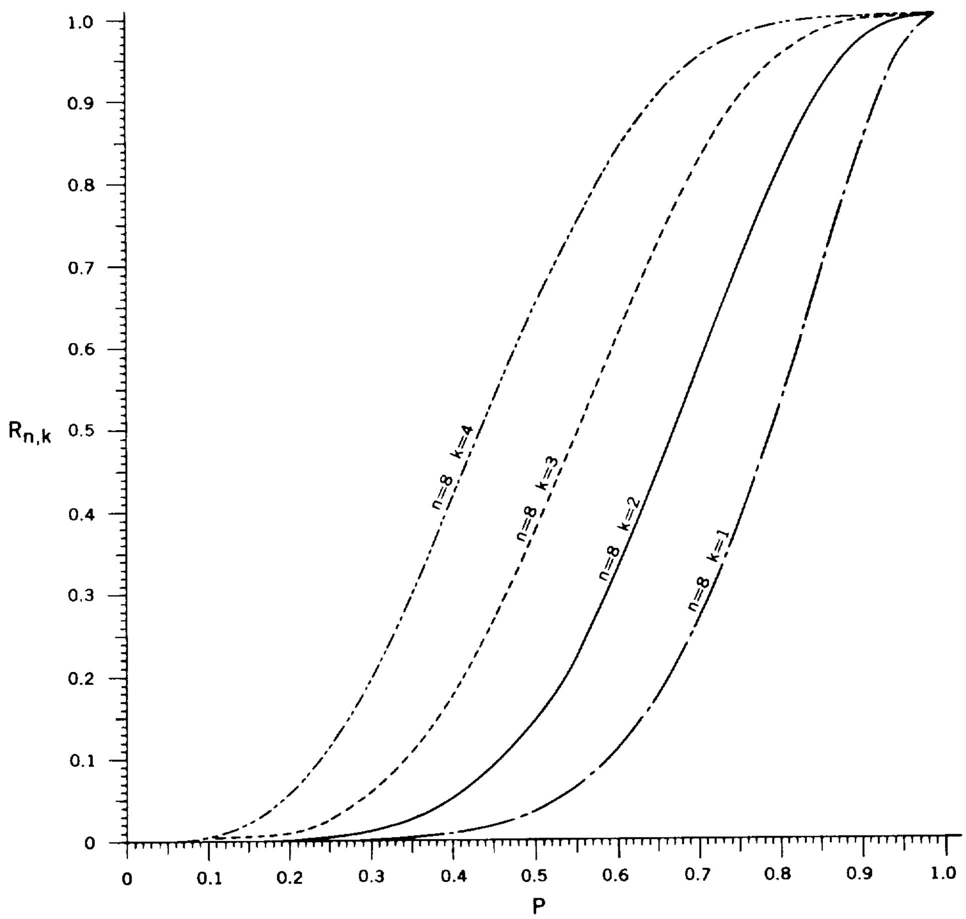

Figure 2—$R_{n,k}$ as a function of P for a constant value of n and a varying value of k

Tables 1 and 2 (which follow the text) give $R_{n,k}$ values as a function of P for a variety of n,k combinations. Values of P in the interval 0.90 to 0.99 are probably of greatest interest and are therefore given separately and in more detail in Table 2.

A spacecraft battery may be designed with either of two objectives in regard to lifetime. The first aims at a maximum probability that the battery will function for a given fixed period of time. The second has as its goal a maximum expected lifetime $(L_{n,k})$. The latter is defined as the average lifetime to be expected of a system containing n strings of which no more than k will fail without causing failure of the system. This value is given by

$$L_{n,k} = \int_0^\infty R_{n,k}(t)\,dt \quad . \tag{2}$$

The term $R_{n,k}(t)$ must be obtained from Equation 1 and entails a knowledge of $P(t)$, i.e., the way that P varies with time.

CONCLUSION

With adequate test results the tabulated data would make it possible to compare $R_{n,k}$ or $L_{n,k}$ values for two or more cell configurations and thus make an optimum choice possible. Unfortunately, the presently available test results are not adequate for this purpose.

The material presented here permits at least one conclusion however. If the P values of two systems are known to be large (close to unity) and approximately the same, it is safe to assume that the larger $R_{n,k}$ value will be obtained with the larger n value; this is apparent from Figure 1 and, of course, assumes the same redundancy (n/k) for the systems being compared.

The tabulated values (Tables 1 and 2) were calculated from data in "Tables of the Binomial Probability Distribution," pages 198-204, U. S. National Bureau of Standards, Applied Mathematics Series 6, Washington, U. S. Government Printing Office, 1950. The function evaluated in these tables is not that given in Equation 1 but is transformed in such a way that (1) for P values from zero to 0.5, $r = n - k$ and $P = p$; and (2) for P values from 0.5 to 1.0, $r = k + 1$ and $P = 1 - p$. Both r and p refer to symbols in the NBS Tables.

ACKNOWLEDGMENT

An independent mathematical analysis was made by Dr. J. R. Rosenblatt of the U. S. National Bureau of Standards. The authors gratefully acknowledge her willing cooperation.

Table 1

Values of $R_{n,k}$ as a Function of P for Various Values of n and k

P	$R_{n,k}$															
	n = 2	n = 3	n = 4		n = 5		n = 6			n = 7			n = 8			
	k = 1	k = 1	k = 1	k = 2	k = 1	k = 2	k = 1	k = 2	k = 3	k = 1	k = 2	k = 3	k = 1	k = 2	k = 3	k = 4
.05	0.09750	0.00725	0.00048	0.01402	0.00003	0.00116	0.00000	0.00009	0.00223	0.00000	0.00001	0.00019	0.00000	0.00000	0.00001	0.00037
.10	0.19000	0.02800	0.00370	0.05230	0.00046	0.00856	0.00005	0.00127	0.01585	0.00001	0.00018	0.00273	0.00000	0.00002	0.00043	0.00502
.15	0.27750	0.06075	0.01198	0.10952	0.00223	0.02661	0.00040	0.00589	0.04734	0.00007	0.00122	0.01210	0.00001	0.00024	0.00285	0.02135
.20	0.36000	0.10400	0.02720	0.18080	0.00672	0.05792	0.00160	0.01696	0.09888	0.00037	0.00467	0.03334	0.00008	0.00123	0.01041	0.05628
.25	0.43750	0.15625	0.05078	0.26172	0.01562	0.10352	0.00464	0.03760	0.16943	0.00134	0.01288	0.07056	0.00038	0.00423	0.02730	0.11382
.30	0.51000	0.21600	0.08370	0.34830	0.03078	0.16308	0.01093	0.07047	0.25569	0.00379	0.02880	0.12604	0.00129	0.01129	0.05797	0.19410
.35	0.57750	0.28175	0.12648	0.43702	0.05402	0.23517	0.02232	0.11742	0.35291	0.00901	0.05561	0.19985	0.00357	0.02532	0.10609	0.29360
.40	0.64000	0.35200	0.17920	0.52480	0.08704	0.31744	0.04096	0.17920	0.45568	0.01884	0.09626	0.28979	0.00852	0.04981	0.17367	0.40591
.45	0.69750	0.42525	0.24148	0.60902	0.13122	0.40687	0.06920	0.25526	0.55848	0.03571	0.15293	0.39171	0.01812	0.08846	0.26038	0.52304
.50	0.75000	0.50000	0.31250	0.68750	0.18750	0.50000	0.10937	0.34375	0.65625	0.06250	0.22656	0.50000	0.03516	0.14453	0.36328	0.63672
.55	0.79750	0.57475	0.39098	0.75852	0.25622	0.59313	0.16357	0.44152	0.74474	0.10242	0.31644	0.60829	0.06318	0.22013	0.47696	0.73062
.60	0.84000	0.64800	0.47520	0.82080	0.33696	0.68256	0.23328	0.54432	0.82080	0.15863	0.41990	0.71021	0.10638	0.31539	0.59409	0.82633
.65	0.87750	0.71825	0.56298	0.87352	0.42841	0.76483	0.31908	0.64709	0.88258	0.23380	0.53228	0.80015	0.16913	0.42781	0.70640	0.89391
.70	0.91000	0.78400	0.65170	0.91630	0.52822	0.83692	0.42017	0.74431	0.92953	0.32942	0.64707	0.87396	0.25530	0.55177	0.80590	0.94203
.75	0.93750	0.84375	0.73828	0.94922	0.63281	0.89648	0.53394	0.83057	0.96240	0.44495	0.75641	0.92944	0.36708	0.67854	0.88618	0.97270
.80	0.96000	0.89600	0.81920	0.97280	0.73728	0.94208	0.65536	0.90112	0.98304	0.57672	0.85197	0.96666	0.50332	0.79692	0.94372	0.98959
.85	0.97750	0.93925	0.89048	0.98802	0.83521	0.97339	0.77648	0.95266	0.99411	0.71658	0.92623	0.98790	0.65718	0.89479	0.97865	0.99715
.90	0.99000	0.97200	0.94770	0.99630	0.91854	0.99144	0.88573	0.98415	0.99873	0.85031	0.97431	0.99727	0.81310	0.96191	0.99498	0.99957
.95	0.99750	0.99275	0.98598	0.99952	0.97741	0.99884	0.96723	0.99777	0.99991	0.95562	0.99624	0.99981	0.94276	0.99421	0.99963	0.99998

Table 2

Values of $R_{n,k}$ as a Function of P for Various Values of n and k

P	$R_{n,k}$															
	n = 2	n = 3	n = 4		n = 5		n = 6			n = 7			n = 8			
	k = 1	k = 1	k = 1	k = 2	k = 1	k = 2	k = 1	k = 2	k = 3	k = 1	k = 2	k = 3	k = 1	k = 2	k = 3	k = 4
.90	0.99000	0.97200	0.94770	0.99630	0.91854	0.99144	0.88573	0.98415	0.99873	0.85031	0.97431	0.99727	0.81310	0.96191	0.99498	0.99957
.91	0.99190	0.97716	0.95704	0.99728	0.93262	0.99366	0.90485	0.98817	0.99915	0.87452	0.98067	0.99816	0.84232	0.97111	0.99659	0.99974
.92	0.99360	0.98182	0.96557	0.99807	0.94564	0.99547	0.92271	0.99149	0.99946	0.89741	0.98599	0.99882	0.87024	0.97890	0.99780	0.99985
.93	0.99510	0.98599	0.97327	0.99870	0.95751	0.99692	0.93918	0.99416	0.99968	0.91873	0.99031	0.99929	0.89653	0.98530	0.99866	0.99992
.94	0.99640	0.98963	0.98009	0.99917	0.96813	0.99803	0.95407	0.99624	0.99982	0.93822	0.99371	0.99961	0.92084	0.99038	0.99925	0.99996
.95	0.99750	0.99275	0.98598	0.99952	0.97741	0.99884	0.96723	0.99777	0.99991	0.95562	0.99624	0.99981	0.94276	0.99421	0.99963	0.99998
.96	0.99840	0.99533	0.99090	0.99975	0.98524	0.99940	0.97845	0.99883	0.99996	0.97062	0.99802	0.99992	0.96185	0.99692	0.99984	0.99999
.97	0.99910	0.99735	0.99481	0.99989	0.99153	0.99974	0.98754	0.99950	0.99999	0.98291	0.99914	0.99997	0.97766	0.99865	0.99995	0.99999
.98	0.99960	0.99882	0.99766	0.99997	0.99616	0.99992	0.99431	0.99985	0.99999	0.99214	0.99974	0.99999	0.98966	0.99958	0.99999	0.99999
.99	0.99990	0.99970	0.99941	0.99999	0.99902	0.99999	0.99854	0.99998	0.99999	0.99797	0.99997	0.99999	0.99731	0.99995	0.99999	0.99999